MMA 2018 FLEXIBLE TECHNOLOGIES

13th INTERNATIONAL SCIENTIFIC CONFERENCE
NOVI SAD, SERBIA, SEPTEMBER 28-29, 2018

Vorkapic , N., Kokotovic, B.

SYNTHESIS AND ANALYSIS OF THE TOOL DYNAMOMETER FOR TURNING OPERATIONS

Abstract: *Virtual manufacturing has predicting of cutting forces in prepared program for CNC machine tool as one of the most important functional block. Development of reliable models of cutting forces requires appropriate sensor technique. It's application is needed in building of data base with specific cutting forces, as well as for evaluation of developed models of cutting forces. Wide use of superior piezo-electric tool dynamometers is significantly reduced because its very high price. Paper presents development of the three- component tool dynamometer with strain gauges. Basic shape of this dynamometer is well known double extended octagonal ring (DEOR). Geometric parameters of the dynamometer body is optimised through FEA analysis. Designed dynamometer achieves partial decomposition of force components. Completing of such force decomposition is realized through decomposition matrix, created using FEA environment.*

Key words*: Cutting forces, Dynamometer, FEA analysis*

1. INTRODUCTION

There are several reasons for applyig of sensors for cutting force measurements. One of them is the need for identification of specific cutting forces in orthogonal cutting, which are necessary for developing of various procedures for predicting of cutting forces and off line optimization of machining process for cetrain parts. For this purpose it is enough to have two-componenet dynamometer. Verification of such procedures and testing of specific tools and machining data also requires dynamometers for cutting forces, but with abillity for measuring more than two components. Developing of procedures for monitoring and on-line adaptive control (AC) of machining processes also need acquisition of cutting force components. The first and the second field of application of dynamometers assume laboratory environment. This paper describes some results in developing of thee-component dynamometer intended for measuring of cutting forces in turning operations. Sensor elements are with resistance strain gauges (RSG).

2. CUTTING FORCE DYNAMOMETERS

Different physical principles for transformation of cutting force in some electrical quantity were used in developing of cutting force dynamometers (CtFD). Among them there are two aproaches which were widely used in recent decades. These are piezoelectric sensors and sensors with resistance strain gauges (RSG). RSG force sensors have: simple construction, high and adjustable resolution , and high reliability [1]. At the same time they have following disandvantages: higher power consumption, lacking reproducibility and, as the most significant, lower stiffness and lower dynamic range.

2.1 Dynamometers with strain gauges

Many of applications of RSG dynamometrs are not too demanding: all what is needed is max permissible load. Linearity, in general case, is sufficient. These are (single component) load cells and weighing devices, sometimes extremely low cost, intended for measuring of static force.

Most of research projects dealing with CtFD use one of three typical design of sensitive elements of dynamometer (Fig.1): specific arrangement of several octagonal rings (OR) [2,3,5,6] , extended octagonal ring (EOR) and double extended octagonal ring (DEOR) [4]. Each of these designs, shown on Fig.1, assumes e areas in which the strain is concentrated.

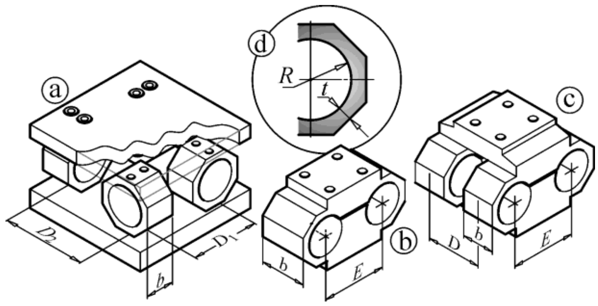

Fig. 1 Typical Sensitive elements of RSG-CtFD and their design parameters

. These are places where RSG should be applied, in such manner that, connected in Wheatston bridge, they enable sufficient level of signal of force component which induces this strain.

Octagonal ring has property of decoupling of two ortogonal force components (directions *n* and *t*) acting opposite from its base Such design is inspired with theory of thin circular rings [2,6], which also have this abillity.This theory shows limitations especially in cases where ratios *t*/*R* increase.

In design of the CtFD, presented in this paper, a DEOR type of sensitive element was used. Reason for such choice was in intention to avoid possible nonlinarities of dynmometer with ORs, caused by nonlinear nature of contact between base, ORs and platform.

3. DESIGN OF TOOL DYNAMOMETER FOR TURNING

In design of tool dynamometer for turning operations, presented in this paper, intention was to satisfy tpical functional requirements:(i) Design of sensitive element which enables measuring of three orthogonal forces in turning up to max values (max F1,F2,F3=5kN, 3kN, 3kN) with pemited overload aprox. 20%, (ii) First modal frequency (with cutting tool) greater than 1000Hz. (iii) Displacement of the tip of CtFD lower than 0.15mm in all coordinate direction in case of simultanous acting of F1,F2,F3=3kN, (iv) Easy exchange and fixing of the turning tool into dynamometer body, (v) CtFD for right hand and lefthand tools, allowing operation in M3/M4 direction of spindle rotation, (vi) Reliable protection from damage (hot chip, coolant) of RSG, their leads and cable to signal conditioning devices.

Design of dynamometer asembly is shown on Fig. 2. Basic part is sensitive (dynamometer body) element (1) DEOR type, symmetric, made of steel, quenched and tempered (*R*m≈950N/mm2). Its base is in form of square flange. Its platform is in form of rigid block with square hole intended for placing of 20x20mm tool shank. Platform (block) is partially separeted from base (flange) with thin cut made with wire EDM. Central hole in the flange is 22x22mm, for free displacement of the rear end of longer tool shank. Concept of this CtFD assumes diferrent adapters for mounting on diferrent tool holders. One example of adapter (3) is shown, with details (4) on flange for its aligning to adapter. Two vertical M8 screws (6) and one screw (5) on side is for fixing of the tool shank in the body.

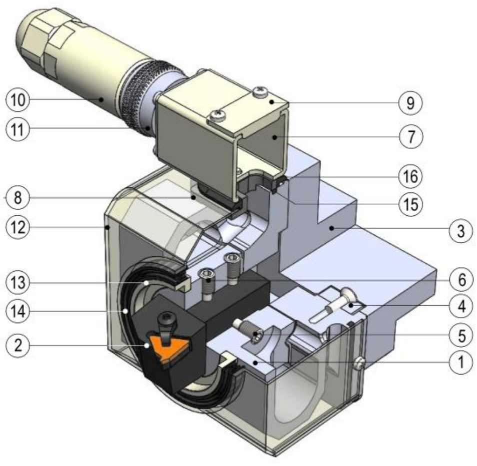

Fig. 2 Assembly of proposed 3-component tool dynamometer for turning

On the top of the body is one terminal box (7) (closed square inox tube) mounted via angular element (8) to the flange of the body. Purpose of terminal box is to offer enough protected space needed for collecting leads from RSG to the connector (11) of the box. Appropriate 12-pin sealed circular cable connector is with modified extension. Such modification was made for relable fixing of three cables (LiYCY 4x0.34) for housing of the connector in corrugated protection steel tube (StaPa 3’’/8). For better approach to numerous RSG leads, there is removable sealed steel cup (9). Protection of RSGs and their leads is raelize using shield (12). Its rear end has square contour for positioning on the flange. Fixing of shield to flange is using 4 screws. Front end of the platfom (block) has presed ring (13) with smal overhang. Radial seal (14) is mounted between this ring and hole in the shield. For sealing between shield and flange of dynamometer body a O-ring (15) was used, placed in the slot on the flange contour. Specific rubber seal (16) is mounted under the terminal box ensuring the sealing between several components (1,7,8,12).

4. DESIGN OF ELASTIC SENSITIVE ELEMENT

Role of cut between tool block and flange is to direct load from tool on half rings (4 rings) making concentrate strain in this part of volume. These 4 rings build DEOR composition. Following paremeters of DEOR were selected: R=12.5mm, t_1=5mm (hrizontal), t_2=6.3mm (inclined), b=24mm, E=40mm and D=54mm (designation acc. Fig 1). Choice of these parameters ssumes compromise between intention to achieve high sensitivity (high level of strain) with low level of displacement (high stiffness is required) at the same time. Generally speaking, these functions for OR [1,6] are in form:

$$\varepsilon_i = \frac{K_{i,\varepsilon} F_i R}{Ebt^2}, \quad \delta_i = \frac{K_{i,\delta} F_i R^3}{Ebt^3} \qquad (1)$$

In choce of parameters R and t, for CtFD, presented here, high stiffness was a priority. Ratio t/R is significantly high (0.504 and 0.4). That implies great stiffness but also lower level of sensitivity and need of higher amplification in devices for signal conditioning.

Significant part of volume of the tool block is removed in order to reduce mass of moving platform without significant decrease of its stiffness. That is very important for keeping modal fequencies of the CtFD sufficiently high.

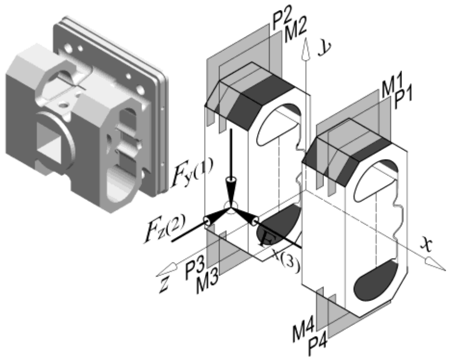

Fig. 3 Sensitive element of proposed dynamometer and cross sections for applying of RSGs

Figure 3 shows solid model of the sensitive element of the CtFD and particular sections of its half-rings. Planes are designated with P(Peripheral) and M(Mid in x dir.) and with number of quadrant of xy plane. These planes are referred as candidate cross sections for applying of RSGs.

Analysis of stresses, strains and dispalcement of the sensitive elements of the CtFD body were performed through FEM simulation (SolidWorks Student Edition). For more precise insight in distribution of strain specific application in Matlab were made. This application uses output files with strain data, from FEM simulation and calculate strain in tangent direction , which is important because RSG is sensitive to deformation in this direction

4.1 FEM analysis

Figure 4 shows, as part of results, distribution of strain ε_{ZZ} in case of F_2 (a) and F_3(b) applied on the tool tip. As the representative tool MTJNR-2020K16 standad holder for turning inserts was chosen (simplified geometry for FEA purposes is shown).

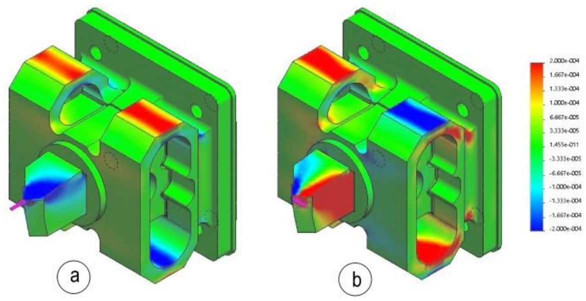

Fig.4 Strain ε_{ZZ} of the CtFD body
Load F_2=3kN(a), Load F_3=3kN(b)

FEM simulation of displacements was separately performed for forces F_1, F_2 and F_3 , applied on the tool tip. For this analysis 2 representative points were chosen: tool tip (TT) and center (BC) of the face of dynamometer body. Based on results of displacement analysis elements $C_{i,j}$[mm/N] of compliance matrices were obtained for these points.

$$C_{TT} = 1E^{-6} * \begin{bmatrix} -78.9 & 4.67 & 6.95 \\ 2.22 & -70.3 & 11.47 \\ 7.27 & 14.56 & -14.55 \end{bmatrix} \quad (2)$$

$$C_{BC} = 1E^{-6} * \begin{bmatrix} -16.05 & -0.23 & 0.95 \\ -0.74 & -25.6 & 1.40 \\ -2.88 & -2.67 & -4.89 \end{bmatrix} \quad (3)$$

Rapid rise of displacements from BC to TT should be treated with some reserve. It can be referred to the great overhanging section of the tool, but it also can be the consequence of the modelling of specific kind of contact between tool and dynamometer body.

	1st Mode [Hz]	2nd Mode[Hz]
CtFDBody + Tool	1395	2135
CtFDBody w/o Tool	1633	2567

Table 1: Frequencies of dominant modes

Dynamic analysis were performed for (i) assembly of dnamometer body with fixed tool and (ii) for dynamometer body without tool. Figure 5 shows mode shapes of the first and second mode obtained through dynamic FEM analysis Mode shapes are similar for both cases (Shear in plane YZ for mode 1, and tilting around Y axis for mode 2). Obtained modal frequencies are shown in Table 1.

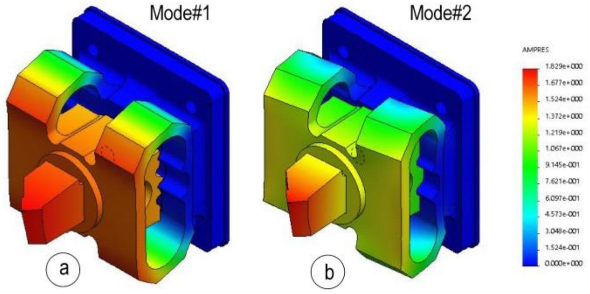

Fig.5 Mode shapes for mode 1 and mode 2.

4.2 Strain analysis in local tangential direction

For correct design of number, arrangement of DMS and its connection in Wheatston bridges for each force component, strain in places of applying RSG, align with its sensitive direction is required. In design of sensor, described in this paper, direction of main sensitivity for each RSGs is assumed to belong one of the planes x=const. Strain FEM analysis in SolidWorks does not offer such kind of results. From this reason, output files with strain analysis ε_x, ε_z and γ_{yz} for simulation of strain for each particular load (F_1, F_2 ,F_3) were exported for use in specific Matlab application, made for this purpose. In this program for each pont of model (in sensitive zones) transformations of strains is performmed in order to calculate strain in direction applying of possible RSG. Calculation of angle θ_N from y+ axis to normal vector of local surface need to be calculated for each point, according to geometry of dynamometer body (Fig .6).

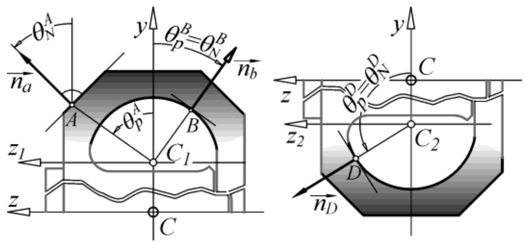

Fig.6 Examples of obtaining angular position of point (θ_P) and angle of local normal vector (θ_N)

Transformation of strains on direction t is calculated according to:

$$\varepsilon_t = \varepsilon_{yy} \sin^2 \theta_N + \varepsilon_{zz} \cos^2 \theta_N - \gamma_{yz} \sin \theta_N \cdot \cos \theta_N$$
(4)

For better presentation of distribution of ε_t, transformation of yz-coordinates of points, on rings, to angular coordinate θ_P was performed. Origin of this polar diagram is either C1 or C2 (axis through centres of inner rings) as shown on Fig 6. FEM analysis of strain and described postprocessing in Matlab of these results were performed for internal (I) and external (E) half-rings of sensor in 4 different cross sections (middle sections: x_{M1}, x_{M2} and peripheral sections: x_{P1}, x_{P2}) according to Fig.3. Results of for mid sections are shown in Figure 7 (I-internal surfaces) and Fig.8 (for E-external surfaces). Results for peripheral planes are not shown here.

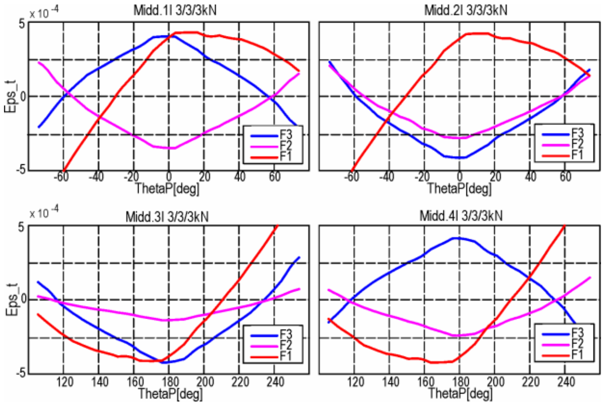

Fig.7 Distribution of ε_t for internal half-rings

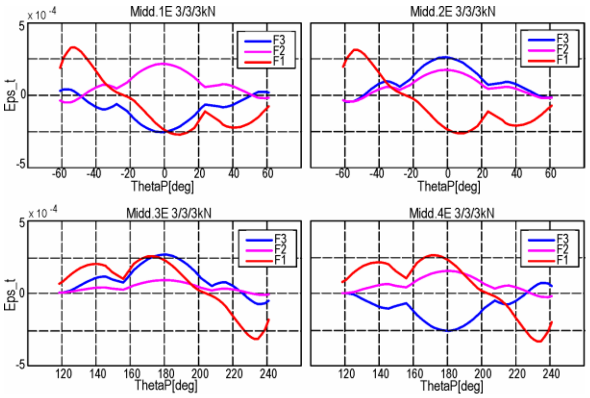

Fig.8 Distribution of ε_t for external half-rings

4.3 Sensitivity and cross-sensitivity

One of the most important performances of multi component CtFD is its ability to achieve reliable decoupling of components of force acting on its sensitive element. Maximum of sensitivities (S_{ii}) and minimum of cross sensitivities (S_{ij}) is required.

$$S_{ii} = \frac{\varepsilon i}{F_i}[\frac{\text{mV}}{\text{V}\cdot\text{N}}],\ S_{ij} = \frac{\varepsilon_i}{F_j}[\frac{\text{mV}}{\text{VN}}] \qquad (5)$$

Several important conclusions, needed for design of RSGs arrangement and its connection in bridges, can be made based on diagrams on Fig.7 and 8. Strain ε_t induced by F_1 (Fig.8) has an asymmetric distribution. Decopupling of F_1 from measured strains seems very simple. Figure 8 shows nodes of deformation ε_t induced by F_2 and F_3 (for values θ_P close to -60°/60° and 117°/227°. Angular positions for RSGs for F_1, near -50°/50° for upper rings, and near 135°/225° are good candidates.

Candidate RSGs for F_2 and F_3 should be placed near θ_P=0° (uppper zone) or θ_P=180° (lower zone), on internal and external surfaces of the half-rings. These locations include huge problem of decoupling of force components. Nodes of $\varepsilon_t(F_1)$ are too far from this location. Additional problem is the fact that both F_2 and F_3 have their extreme values around these locations. Possible sulution is specif-ic connection of RSGs in branches of the bridge. That means 2 RSGs (with same sign of strain) in series in each branch.

Analysis based on results shown on Fig.7 and 8, with specific connection of RSGs, for each component enables calculation of elements of sensitivity matrix:

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} = 10^{-9}\begin{bmatrix} 183 & 0 & 0 \\ 6.25 & 139 & 4.16 \\ 2.08 & 22.6 & 159 \end{bmatrix} \qquad (6)$$

Max absolute value of ratio S_{ii}/S_{ij} is 14%. Such result implies good decoupling performances of designed dynamometer, but also implies need for software decoupling using inverse of S. Relatively lower level of direct sensitivities is consequence of intention to keep high stiffness of dynamometer body.

5. CONCLUSION

Very good performances (strain, stiffness, sensitivity) in analysis of presented design of 3 component RSG tool dynamometer for turning, were shown. It is expected that prototype of this dynamometer will be useful in experimental activities referred to cutting force measurements. Final estimation of its performances needs to be obtained through experiments. One of the future tasks is obtaining of maps of these performances for different tools, regarding eccentricity of their tips.

6. REFERENCES

[1] Soliman, E., *Performance analysis of octal rings as mechanical force transducers*, Alexandria Engineering Journal, 2015, Vol.54, pp.155–162.

[2] Yaldiz,S., *Development and Testing of a Cutting Force Dynamometer for Milling*, Journal of Polytechnic, 2005, Vol. 8, No. 1, pp. 61-68.

[3] Yaldiz, S., Unsacar, F., *A dynamometer design for measurement the cutting forces on turning*, Measurement, Vol. 39, pp. 80-89, 2006.

[4] McLaughlin, N.B., Tessier,S., Guilbert, A., *Improved double extended octagonal ring drawbar transducer for 3-D force measurement*, Canadian Agricultural Engineering, 1998, Vol. 40, No.4, pp.257-264.

[5] Zhao,Y., S. Liang,S., Zhou, G., *A High Performance Sensor for Triaxial Cutting Force Measurement in Turning*, Sensors, 2015,Vol.15, 7969-7984.

[6] Uddin, M.S., Songyi ,D., *On the design and analysis of an octagonal–ellipse ring based cutting force measuring transducer*, Measurement, 2016, Vol. 90, pp. 168–177..

Authors: **Nikola Vorkapic Ph.D. student, Assist. Prof. Branko Kokotovic,** University of Belgrade, Mechanical Engineering Faculty, Department of Production Engineering, Kraljice Marije 16, 11000 Belgrade, Serbia, Phone.: +381 11 3302-375, Fax: +381 11 3370-364.
E-mail:nikola.vorkapic92@gmail.com
bkokotovic@mas.bg.ac.rs;

ACKNOWLEDGMENTS: The authors would like to thank the Ministry of Education, Science and Technological Development of Serbia for providing financial support that made this work possible.